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Centrality dependence of the charged-particle multiplicity density at mid-rapidity in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

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Abstract

The pseudorapidity density of charged particles, $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$, at mid-rapidity in Pb–Pb collisions has been measured at a center-of-mass energy per nucleon pair of $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. For the 5% most central collisions we measure a value of 1943 ± 54. The rise in $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ as a function of $\sqrt{s_{\mathrm{NN}}}$ is steeper than that observed in proton–proton collisions and follows the trend established by measurements at lower energy. The increase of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ as a function of the average number of participant nucleons, $\langle N_{\mathrm{part}} \rangle$, calculated in a Glauber model, is compared with the previous measurement at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. A constant factor of about 1.2 describes the increase in $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ from $\sqrt{s_{\mathrm{NN}}} = 2.76$ to 5.02 TeV for all centrality classes, within the measured range of 0–80% centrality. The results are also compared to models based on different mechanisms for particle production in nuclear collisions.

*See Appendix A for the list of collaboration members

The theory describing the strong interaction, quantum chromodynamics (QCD), predicts the existence of a deconfined phase of matter, the quark-gluon plasma, at high temperature and energy density. Ultra-relativistic collisions of nuclei achieve the conditions necessary for the formation of this strongly interacting matter [1, 2].

The multiplicity of produced particles is an important property of the collisions related to the collision geometry, the initial parton densities and the energy density produced. Its dependence on the impact parameter is sensitive to the interplay between particle production from hard and soft processes and coherence effects between individual nucleon–nucleon scatterings. With an increase in the collision energy, the role of hard processes i.e. parton scatterings with large momentum transfer, increases. After a two-year long shutdown, the Large Hadron Collider (LHC) restarted operation in June 2015 and produced Pb–Pb collisions at a per nucleon center-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV in November 2015. This is the highest energy achieved in the laboratory to date and offers the possibility to further constrain particle production models by studying their $\sqrt{s_{\mathrm{NN}}}$ dependence.

Collisions of extended objects such as nuclei can be classified according to their centrality, which is related to the overlap area of the nuclei. This results in different numbers of nucleons participating in the collision. The number of these participants, N_{part}, can be calculated by a Monte Carlo (MC) sampling technique in the Glauber model [3].

Previous measurements of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ for nucleus–nucleus (AA) collisions were performed at the LHC by ALICE [4], ATLAS [5] and CMS [6] at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV and at lower energies, in the range $\sqrt{s_{\mathrm{NN}}} = 9$ to 200 GeV, with experiments at the Super Proton Synchrotron (SPS) and Relativistic Heavy Ion Collider (RHIC) [7–12]. They show that the increase of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ with energy is steeper in nucleus-nucleus compared to proton–proton collisions. The centrality dependence of $\frac{2}{\langle N_{\mathrm{part}}\rangle}\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta\rangle$ in Pb–Pb at $\sqrt{s_{\mathrm{NN}}} =$ 2.76 TeV is very similar to that measured in $\sqrt{s_{\mathrm{NN}}} = 200$ GeV collisions at RHIC, pointing to a similar mechanism of particle production at the two energies.

In this Letter we present the measurement of the charged-particle pseudorapidity density averaged in the interval $|\eta| < 0.5$, $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta\rangle$, and its centrality dependence. The pseudorapidity is defined by $\eta = -\ln\tan(\theta/2)$, with θ the emission angle of the particle relative to the beam axis. The primary charged particles are defined as prompt particles produced in the collision including all decay products, except products from weak decays of light flavor hadrons and of muons.

The data were recorded with the ALICE detector in November 2015 at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. Full details on the ALICE apparatus [13] and its operational performance [14] are given elsewhere. A brief description of the most relevant elements, along with the experimental conditions, follows. The observed interaction rate was around 300 Hz, of which about 25 Hz were from hadronic interactions, the remainder being a background from electromagnetically induced processes. A total of about 10^5 hadronic events are used. The interaction probability per bunch-crossing (during which bunches of ions from each beam are arranged to be co-incident at the ALICE interaction point) was sufficiently small that the chance of two hadronic interactions occurring together, so-called pileup events, was negligible.

The measurement relies on the ALICE Inner Tracking System, the innermost two layers of which form the Silicon Pixel Detector (SPD). It consists of arrays of pixels arranged with an approximate cylindrical geometry at radii of 3.9 and 7.6 cm covering intervals of $|\eta| < 2.0$ and $|\eta| < 1.4$ for the inner and outer layers, respectively. The SPD is situated in a solenoidal magnet, with its principal axis along the beam line, providing a 0.5 T magnetic field. The interaction trigger is provided by two detectors, V0A and V0C, which consist of arrays of scintillators, covering the full azimuth and more than 4 units of pseudorapidity, in the ranges $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$, respectively. In all cases the η-coverage refers to collisions at the nominal interaction point. A signal must be present in both V0 detectors to trigger the recording of the interaction. The V0 detectors also provide a signal proportional to the number of charged particles striking them which is used to classify the events into centrality classes, defined in terms of percentiles of the hadronic cross-section. In addition, an offline event selection employs the information from two Zero Degree Calorimeters (ZDC) positioned 112.5 m from the interaction point on either side. Beam background events are removed using the V0 timing information and the correlation between the sum and the difference of times measured in each of the ZDCs [14].

The analysis is restricted to the 80% most central events. The classification of events into centrality classes is done by using the summed amplitudes of the signals in the V0A and V0C detectors, following the method developed previously [15, 16]. The V0 amplitude is fitted with an MC implementation of the Glauber model coupled with a two-component model assuming that the effective number of particle-producing sources is given by $f \times N_{\mathrm{part}} + (1-f) \times N_{\mathrm{coll}}$, where N_{part} is the number of participating nucleons, N_{coll} is the number of binary nucleon–nucleon collisions and $f \approx 0.8$ quantifies their relative contributions. The number of particles produced by each source is distributed according to a Negative Binomial Distribution (NBD), parametrised with μ and k, where μ is the mean multiplicity per source and k controls the contribution at high multiplicity. In the Monte Carlo Glauber calculation, the nuclear density for ^{208}Pb is modeled by a Woods–Saxon distribution for a spherical nucleus with a radius of 6.62 ± 0.06 fm and a skin thickness of 0.546 ± 0.010 fm, based on data from low energy electron–nucleus scattering experiments [17], and a hard-sphere exclusion distance between nucleons of 0.4 ± 0.4 fm. For $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV collisions, an inelastic nucleon–nucleon cross-section of 70 ± 5 mb, obtained by interpolation [18], is used. The fit was restricted to a region where the effects of trigger inefficiency and contamination by electromagnetic processes are negligible. The NBD-Glauber fit provides a good description of the observed V0 amplitude in this region, which corresponds to the most central 90% of the cross-section. All events in the sample corresponding to 0–80% of the hadronic cross section are found to have a well-defined primary vertex, extracted by correlating hits in the two SPD layers.

The $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ measurement is performed using short track segments, termed tracklets [19]. Tracklet candidates are formed using the position of the primary vertex and a pair of hits, one in each SPD layer. For each of the hits in the pair two angles are determined with respect to the reconstructed interaction vertex and the angular differences, $\Delta\varphi$ in the bending plane and $\Delta\theta$ in the polar direction, are calculated for each pair of hits. In order to reject candidates produced by the random combination of two hits, tracklets are selected by a cut on the sum of the squares, $\delta^2 = (\Delta\varphi/\sigma_\varphi)^2 + (\Delta\theta/\sigma_\theta)^2 < 1.5$, where $\sigma_\varphi = 60$ mrad and $\sigma_\theta = 25\sin^2\theta$ mrad. This selection effectively allows the reconstruction of charged particles with transverse momentum (p_{T}) above the 50 MeV/c cut-off determined by particle absorption in the material.

The acceptance region in η depends on the position of the interaction vertex along the beamline, z. Events with $|z| < 7$ cm are used, corresponding to a coverage of $|\eta| < 0.5$ with an approximately constant acceptance.

A correction is needed to account for the acceptance and efficiency of a primary track to generate a tracklet, including the extrapolation to zero p_{T}, and for the removal of combinatorial background tracklets. This is computed using simulated data from the HIJING event generator [20] transported through a GEANT3 [21] simulation of ALICE, where the centrality definition is adjusted so that the particle density is similar to that in real data for the same centrality classes. A re-weighting of the generator output is performed to reproduce the p_{T} distributions of inclusive charged hadrons and the relative abundances of pions, protons, kaons and other strange particles as measured in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV [22–25]. Using results from $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV is justified because the relative abundances at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV change very little from those at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV. Any variation with the increase in $\sqrt{s_{\mathrm{NN}}}$ to 5.02 TeV will be much smaller than the differences between the default and re-weighted HIJING simulations, which lead to differences in the results within the systematic uncertainties estimated below.

The correction takes into account any inactive channels present at the time of data taking as well as

Centrality	$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}$	N_{part}	$\frac{2}{N_{\mathrm{part}}}$ $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}$
0–2.5%	2035 ± 52	398 ± 2	10.2 ± 0.3
2.5–5.0%	1850 ± 55	372 ± 3	9.9 ± 0.3
5.0–7.5%	1666 ± 48	346 ± 4	9.6 ± 0.3
7.5–10%	1505 ± 44	320 ± 4	9.4 ± 0.3
10–20%	1180 ± 31	263 ± 4	9.0 ± 0.3
20–30%	786 ± 20	188 ± 3	8.4 ± 0.3
30–40%	512 ± 15	131 ± 2	7.8 ± 0.3
40–50%	318 ± 12	86.3 ± 1.7	7.4 ± 0.3
50–60%	183 ± 8	53.6 ± 1.2	6.8 ± 0.3
60–70%	96.3 ± 5.8	30.4 ± 0.8	6.3 ± 0.4
70–80%	44.9 ± 3.4	15.6 ± 0.5	5.8 ± 0.5

Table 1: The $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}$ and $\frac{2}{N_{\mathrm{part}}}$ $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}$ values measured in $| \ | < 0.5$ for eleven centrality classes. The values of N_{part} obtained with the Glauber model are also given. The errors are total uncertainties, the statistical contribution being negligible.

losses due to physical processes like absorption and scattering, which may result in a charged particle not creating a tracklet. The fractions of active pixels in the inner and outer SPD layers were about 85% and 97.5%, respectively. The estimated combinatorial background amounts to about 18% in the most central (0–2.5%) and 1% in the most peripheral (70–80%) centrality classes. A correction of about 2% for contamination by secondaries from weak decays is applied based on the same simulation.

Several sources of systematic uncertainty were investigated. The centrality determination introduces an uncertainty via the fitting of the V0 amplitude distribution to the hadronic cross-section, due to the contamination from electromagnetically induced reactions at small multiplicity. The fraction of the hadronic cross-section (10%) at the lowest multiplicity, where the trigger and event selection are not fully efficient and the contamination is non-negligible, was varied by an uncertainty of $\pm 0.5\%$. This uncertainty was estimated by varying NBD-Glauber fitting conditions and by fitting a different centrality estimator, based on the hits in the SPD. The uncertainty from the centrality estimation results in an uncertainty of 0.5% for central 0–2.5% collisions, increasing in the more peripheral collision classes, reaching 7.5% for the 70–80% sample, where it is the largest contribution. Conversely, the uncertainty due to the subtraction of the background is largest for the central event sample, where it is about 2%, and becomes smaller as the collisions become more peripheral, amounting to only 0.2% for the 70–80% event class. This uncertainty is estimated by using an alternative method where fake hits are injected into real events.

All other sources of systematic uncertainty are independent of centrality. The uncertainty resulting from the subtraction of the contamination from weak decays of strange hadrons is estimated, from the tuned MC simulations, to amount to about 0.5% by varying the strangeness content by $\pm 30\%$. The uncertainty due to the extrapolation down to zero p_{T} is estimated to be about 0.5% by varying the number of particles below the 50 MeV/c low-p_{T} cut-off by $\pm 30\%$. An uncertainty of 1% for variations in detector acceptance and efficiency was evaluated by carrying out the analysis for different slices of the z-position of the interaction vertex distribution and with subsamples in azimuth.

Other effects due to particle composition, background events, pileup, material budget and tracklet selection criteria were found to be negligible. The final systematic uncertainties assigned to the measurements are the quadratic sums of the individual contributions, and range from 2.6% in central 0–2.5% collisions to 7.6% in 70–80% peripheral collisions, of which 2.3% and 7.5%, respectively, are centrality dependent and 1.2% are centrality independent.

The results for $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}$ are shown in Table 1. In order to compare bulk particle production at different energies and in different collision systems, specifically for a direct comparison to pp and p$\overline{\mathrm{p}}$ collisions,

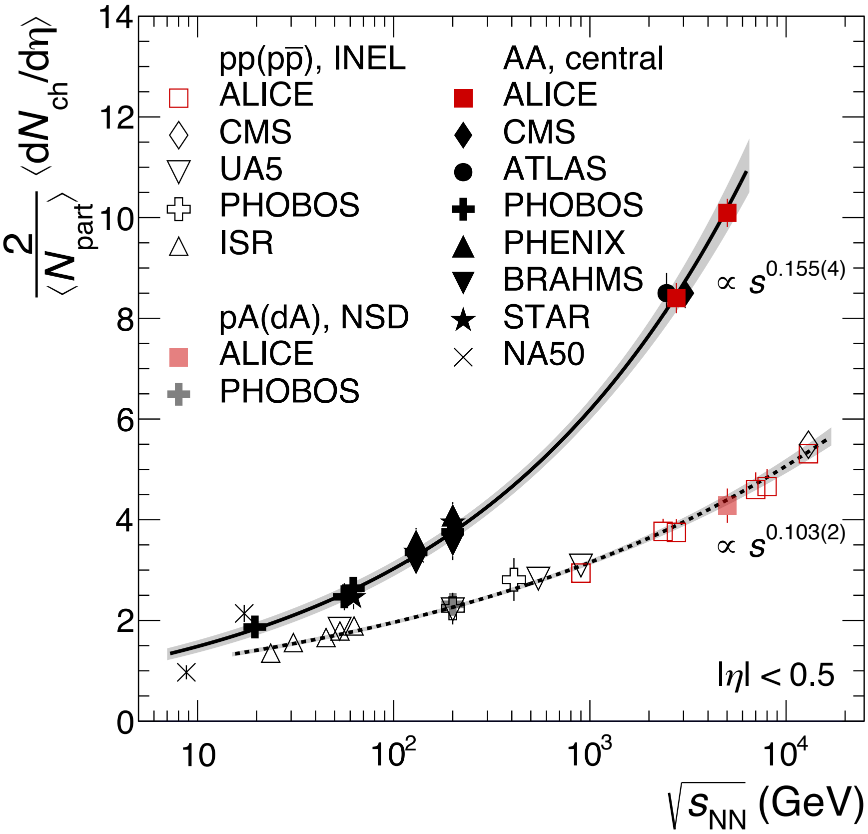

Fig. 1: Values of $\frac{2}{N_{\mathrm{part}}}$ $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}$ for central Pb–Pb [4–7] and Au–Au [8–12] collisions (see text) as a function of s_{NN}. Measurements for inelastic pp and pp̄ collisions as a function of s are also shown [26–28] along with those from non-single diffractive p–A and d–A collisions [29, 30]. The s-dependencies of the AA and pp (pp̄) collision data are well described by the functions $s_{\mathrm{NN}}^{0.155}$ (solid line) and $s_{\mathrm{NN}}^{0.103}$ (dashed line), respectively. The shaded bands show the uncertainties on the extracted power-law dependencies. The central Pb–Pb measurements from CMS and ATLAS at 2.76 TeV have been shifted horizontally for clarity.

the charged-particle density is divided by the average number of participating nucleon pairs, N_{part} /2. The N_{part} values are calculated with an MC-Glauber for centrality classes defined by classifying the events according to their impact parameter and are also listed in Table 1. The systematic uncertainty on N_{part} is obtained by independently varying the parameters of the Glauber model within their estimated uncertainties. For the most central 0–5% collisions, a density of primary charged particles at mid-rapidity $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}$ $= 1943 \pm 54$ was measured and, normalized per participant pair corresponds to $\frac{2}{N_{\mathrm{part}}}$ $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}$ $= 10.1 \pm 0.3$. In Figure 1 this value is compared to the existing data for central Pb–Pb and Au–Au collisions from experiments at LHC [4–6], RHIC [8–12] and SPS [7]. The data shown are for 0–5% except for the results from PHOBOS [11] and ATLAS [5] which are for 0–6%. The dependence of $\frac{2}{N_{\mathrm{part}}}$ $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}$ on the center-of-mass energy can be fitted with a power law of the form $a \cdot s^b$. This gives an exponent, under the assumption of uncorrelated uncertainties, of $b = 0.155 \pm 0.004$. It is a much stronger s-dependence than for proton–proton collisions, where a value of $b = 0.103 \pm 0.002$ is obtained from a fit to the same function [28]. The fit results are plotted with their uncertainties shown as shaded bands. The result at s_{NN} = 5.02 TeV confirms the trend established by lower energy data since b is not significantly different when the new point is excluded from the fit. It can also be seen in the figure that the values of $\frac{2}{N_{\mathrm{part}}}$ $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}$ measured by ALICE for p–Pb [18] and PHOBOS for d–Au [11] collisions fall on the curve for proton–proton collisions, indicating that the strong rise in AA is not solely related to

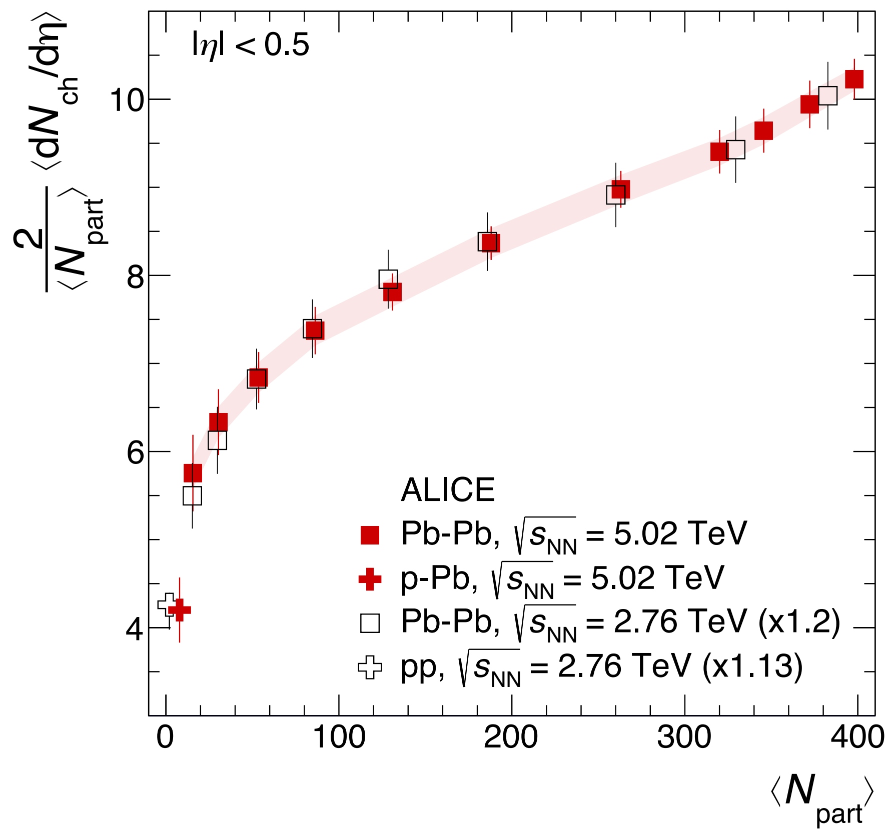

Fig. 2: The $\frac{2}{N_{\mathrm{part}}}$ $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}$ for Pb–Pb collisions at s_{NN} = 5.02 TeV in the centrality range 0–80%, as a function of N_{part} in each centrality class. The error bars indicate the point-to-point centrality-dependent uncertainties whereas the shaded band shows the correlated contributions. Also shown is the result from non-single diffractive p–Pb collisions at the same s_{NN} [18]. Data from lower energy (2.76 TeV) Pb–Pb and pp collisions [4, 26], scaled by a factor of 1.2 and 1.13 respectively, are shown for comparison. The error bars for p–Pb at s_{NN} = 5.02 TeV and lower energy Pb–Pb and pp collisions indicate the total uncertainty.

the multiple collisions undergone by the participants since the proton in p–A collisions also encounters multiple nucleons.

The centrality dependence of $\frac{2}{N_{\mathrm{part}}}$ $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}$ is shown in Figure 2. The point-to-point centrality-dependent uncertaintes are indicated by error bars whereas the shaded bands show the correlated contributions. The statistical uncertainties are negligible. The data are plotted as a function of N_{part} and a strong dependence is observed, with $\frac{2}{N_{\mathrm{part}}}$ $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}$ decreasing by a factor 1.8 from the most central collisions, large N_{part} , to the most peripheral, small N_{part} . There appears to be a smooth trend towards the value measured in minimum bias p–Pb collisions [18]. The Pb–Pb data measured at s_{NN} = 2.76 TeV [4] are also shown, scaled by a factor 1.2, which is calculated from the observed $s^{0.155}$ dependence of the results in the most central collisions, and which describes well the increase for all centralities. The proton–proton result at the same energy [26] is scaled by a factor 1.13 from the $s^{0.103}$ dependence. The ratio between the data measured at the two collision energies is consistent with being independent of N_{part}, within the uncertainties, which are largely uncorrelated. While in general the uncertainties related to the tracklet measurement are correlated between the two analyses, the subtraction of the background and the centrality classification are, instead, uncorrelated, depending on the determination of the usable fraction of the hadronic cross-section and therefore on the run and detector conditions [15].

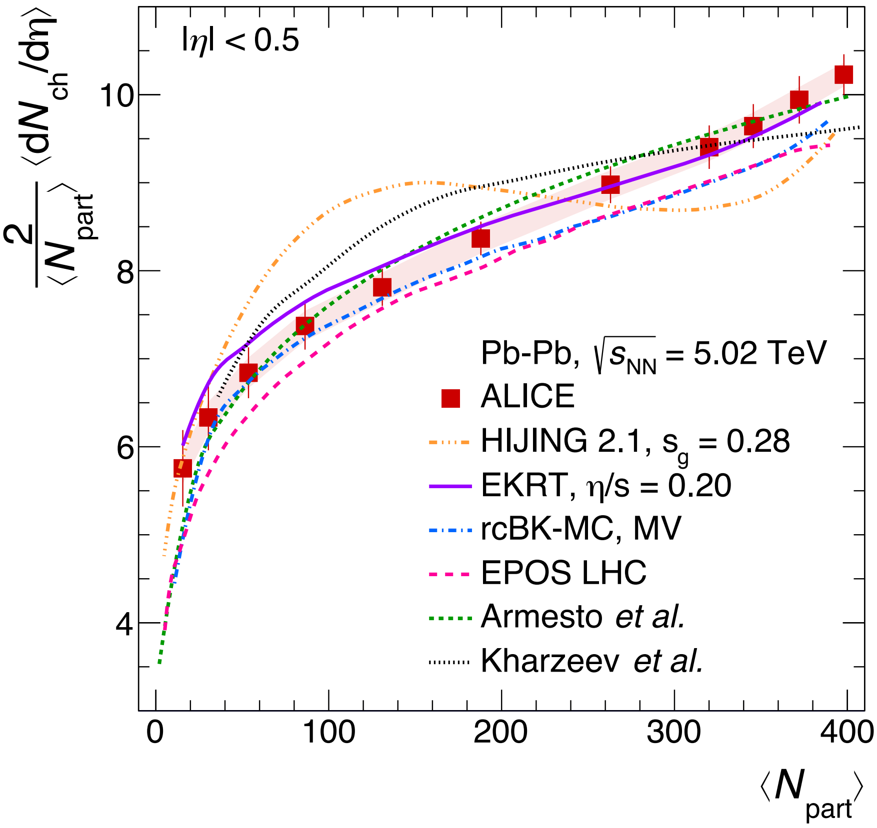

Fig. 3: The $\frac{2}{N_{\mathrm{part}}}$ $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}$ for Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV in the centrality range 0-80%, as function a of N_{part} in each centrality class, compared to model predictions [31–39].

Figure 3 shows a comparison of the data to some of the models which were compared to the measurements at lower energy. The curves shown are predictions of the models, without any retuning of the parameters based on the new data presented here.

Predictions from commonly used Monte Carlo generators, HIJING [33] and EPOS LHC [39], are also shown. HIJING combines perturbative-QCD (pQCD) processes with soft interactions, and includes a strong impact parameter dependence of parton shadowing. The data at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV were previously compared to HIJING using gluon shadowing parameter, s_g, values of 0.20 and 0.23 [4]. The higher value gave a better estimate of the overall normalization, the lower one a better agreement with the shape. At $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV a larger s_g value of 0.28 is required to limit the multiplicity per participant, leading to a centrality dependence which does not reproduce the data. EPOS is a model based on the Gribov-Regge theory at parton level which incorporates collective effects treated via a flow parametrisation in the EPOS LHC version. It provides a good description of the data.

Saturation-inspired models (rcBK-MC, with the MV initial conditions [35, 36], Kharzeev *et al.* [38] and Armesto *et al.* [37]) rely on pQCD and use an initial-state gluon density to fix an energy-dependent scale at which the quark and gluon densities saturate thereby limiting the number of produced partons and, in turn, of particles. This results in a factorization of the energy and centrality dependences of the multiplicity in the models, as observed in the experimental data. The rcBK-MC and Armesto *et al.* models provide a better description of the data, in particular of the shape, than the Kharzeev *et al.* model.

The EKRT model [31, 32] combines collinearly factorized next-to-leading order pQCD mini-jet cross sections with a conjecture of gluon saturation to suppress soft parton production. Impact-parameter dependent EPS09s parton distribution functions [40] are used. The space-time evolution of the system with the computed initial conditions is described with relativistic viscous hydrodynamics event-by-event. The normalization is fixed by exploiting the 0–5% most central multiplicity measurement [19]. The EKRT model can broadly describe both the shape and the overall magnitude of the dependence of multiplicity on centrality. In general, theoretical models need some sort of mechanism to limit the growth of multiplicity in order to describe the centrality and energy evolution of the multiplicity.

In summary, we have measured the charged-particle pseudorapidity density $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}$ in Pb–Pb collisions at the highest available center-of-mass energy and observe a 20% increase for the most central collisions with respect to similar measurements at 2.76 TeV, in agreement with the previously established power-law dependence of this quantity. The centrality dependence of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}$ is very similar to that previously measured in lower energy AA collisions, with a factor of 1.8 increase from peripheral to central collisions. Most of the models which were able to reproduce the data at $\overline{s_{\mathrm{NN}}}$ = 2.76 TeV are able to describe the data at $\overline{s_{\mathrm{NN}}}$ = 5.02 TeV. Our results provide further constraints for models describing high-energy heavy-ion collisions.

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A The ALICE Collaboration

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